Investigation of the Unique Cryogenic Pumping System of the CHAFF-IV Spacecraft-Thruster Interaction Facility

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Abstract. Chamber –IV of the Collaborative High Altitude Flow Facility was designed to obtain high fidelity spacecraft-thruster interaction data. CHAFF-IV uses a total chamber pumping concept by lining the entire chamber with an array of cryogenically cooled, radial fins. Details of Monte Carlo numerical simulation and experimental investigation of the radial fin target array pumping efficiency are presented.

INTRODUCTION

Interactions between propulsion system effluents and sensitive surfaces have received considerable interest within the spacecraft community in recent years. The impact of potential interactions is becoming more critical as mission life and payload sensitivity requirements increase. The adsorption of propellant gases on spacecraft surfaces can change the spectral absorptivity of thermal control surfaces, alter reflectivity of optical surfaces, alter transmission through solar cell coverglass, and induce environments that can alter scientific results. Ion electric thrusters add further complications due to material sputtering from high energy propellant impact and the possible alteration of spacecraft potentials.

Because of the cost and time requirements associated with space-based experiments, ground-based examination of spacecraft-thruster interactions is necessary to compliment the limited data returned from space. In order for ground-based experiments to be effective, facilities must faithfully and consistently reproduce the space environment. The major limitation of ground facilities in accurately predicting the effects of thruster operations on spacecraft systems has been driven by the facility background pressure. Although some fraction of the background gas is composed of the residual laboratory atmosphere, the largest complication arises from the fact that the overwhelming majority of the background pressure is thruster derived. These thruster-borne components are largely responsible for experimental measurement errors. Minimizing the effects of these effluents on interaction results requires extremely high pumping rates; therefore, improvements in the accuracy of ground-based interaction data come at the expense of more efficient chamber pumping. A general review of interaction facilities and advanced pumping concepts has been compiled by Ketsdever. [1]

Chamber IV of the David P. Weaver Collaborative High Altitude Flow Facility (CHAFF) was designed in an effort to obtain meaningful spacecraft-thruster interaction data by maximizing the facility's high vacuum pumping. [2] As shown in Figures 1 and 2, CHAFF-IV incorporates a total chamber pumping (TCP) concept by lining the entire facility with an array of cryogenically cooled, radial fins. The aluminum finned arrays are contained inside a 3m diameter by 6m long stainless-steel vacuum chamber. Details of the initial investigation of CHAFF-IV's cryogenic pumping system are presented along with results from a simple Monte Carlo numerical model. For the experiment, the target section of the radial fin array and a simple flat panel have been independently investigated.

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Both pumping configurations were cooled to liquid nitrogen (LN2) temperatures (77-80K) with a sonic orifice introducing a carbon dioxide gas flow on the axis of the chamber.

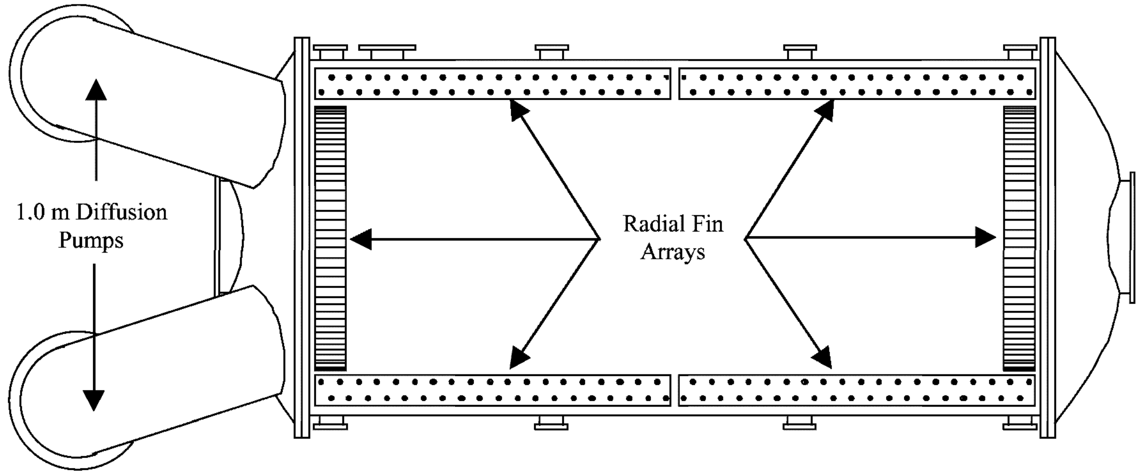
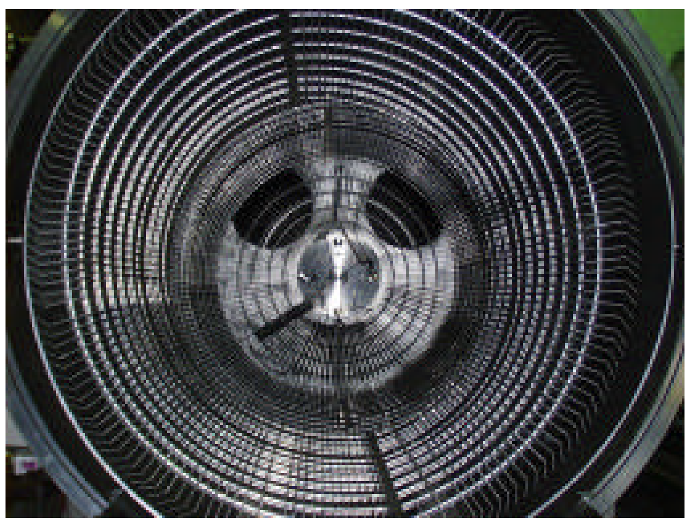


FIGURE 1. CHAFF-IV Cryogenically Cooled, Radial Fin Total Chamber Pumping Arrangement.



FACILITY BACKGROUND PRESSURE REQUIREMENTS

In a typical ground-based facility with a small fraction f_p of its inner surface occupied by pump inlets, the thruster effluents are typically stopped and randomized by the facility's surfaces. The random motion of the scattered propellant molecules inefficiently brings them to a pump inlet. The background pressure of the propellant gas can be approximated by

$$p_b = \frac{4\dot{M}k\sqrt{T_b T_p}}{mv' f_p A_s} = \frac{\dot{M}kT_b}{m\dot{V}} \tag{1}$$

were $\dot{M}$ is the propellant mass flow, k is Boltzmann's constant, T_b and T_p are the background and propellant gas temperatures respectively, m is the molecular mass of the propellant gas, v' is the average thermal speed of the background gas, f_p is the fraction of the facility inner surface occupied by pump inlets or pumping surfaces, A_s is the inner surface area of the facility, and $\dot{V}$ is the facility's pumping speed. In order to minimize the effects of chamber induced charge exchange collisions in xenon ion thrusters, background pressures on the order of 3 x 10^{-6} Torr are

required. [1] For a typical Hall thruster propellant mass flow rate of 5 mg/s, Eq. (1) indicates that pumping rates in excess of 2.5 x 10^5 L/s are required. For a cold gas system with a nitrogen propellant flow rate of 1 g/s, pumping rates on the order of 10^7 L/s are required to maintain free molecular flow in the plume backflow region.

Clearly a critical background number density for thruster plume interaction studies is reached when the background mean free path becomes less than or equal to the largest internal dimension of the facility L_c. Therefore, the background number density should be

$$n_b \leq \frac{1}{\sqrt{2}\sigma_b L_c} \tag{2}$$

where σ_b is the background gas collision cross section and λ_c is the critical mean free path.

As Eq. (1) indicates, background gas pressure can be minimized by having large available pumping areas (f_pA_s). For a given chamber geometry, the pumping rate is maximized by increasing the fraction of the inner surface area which acts as a pump. This suggests that high pumping rates can be achieved when the entire inner surface of the facility is a pumping surface. The TCP concept has driven the design of several interaction facilities. [2-4]

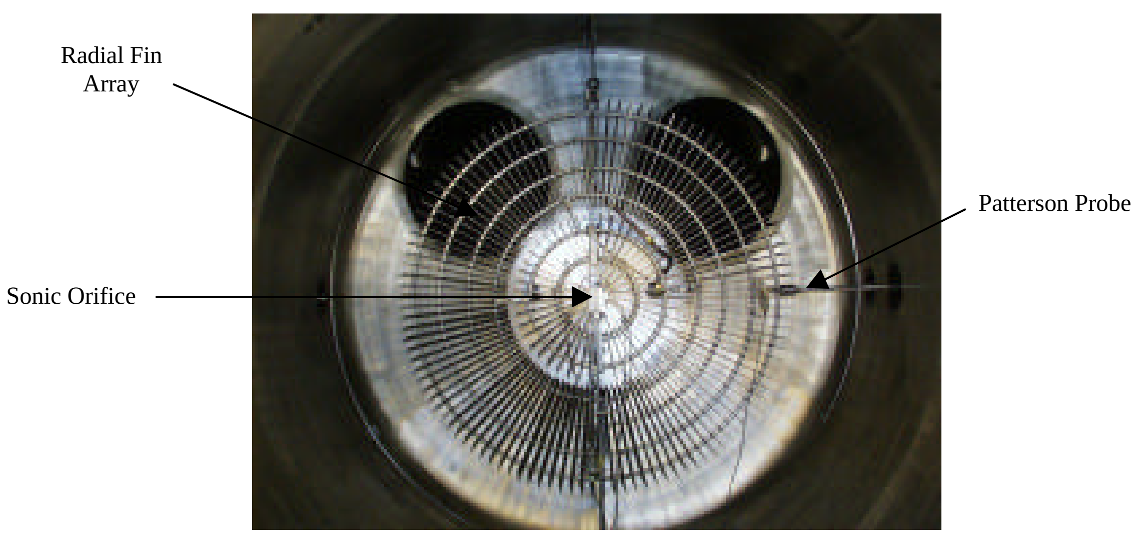
For the radial fin TCP array, the fraction of efflux from a thruster impinging on the array that is able to return to the thruster vicinity is given by

$$F_r = (1-\eta)\left[\frac{w^2}{2h(w+t)} + \frac{t}{(w+t)}\right]\left(\frac{D_o}{X}\right)^2 \tag{3}$$

where η is the sticking coefficient, w is the radial fin-to-fin spacing, h is the length of the fin in the axial direction, t is the fin thickness, D_o is the characteristic thruster diameter, and X is the distance from the thruster exit plane to the front edge of the radial fin array. Design of the radial fin arrays can be optimized through the minimization of the geometric term in the brackets of Eq. (3) by an appropriate selection of the fin geometry. For the CHAFF-IV radial fin target array, h = 25.4 cm, t = 0.32 cm, and w varies from 1 to 6 cm due to the radial nature of the array.

EXPERIMENT

In order to determine the pumping capabilities of the 112 fins that make up the target section array shown in Fig. 3, LN_2 was used to cool the panels while CO_2 gas was introduced on the chamber centerline. Carbon dioxide pumping at LN_2 surface temperatures of ~80 K was used to simulate other gases (including xenon) pumping on 15-20 K surfaces since the sticking coefficients are similar as shown in Table 1. [5]



For the radial fin configuration, the CO_2 was introduced into the chamber through a sonic orifice (diameter = 0.178cm) on the chamber centerline located 79.1cm from the front of the array as shown in Fig. 4(a). The density of the free jet flow field decreases as the inverse square of the distance x from the source as measured along a streamline. The number density also varies from streamline to streamline. The number density as a function of position from the sonic orifice is given by [6]

$$n(x, 0) = n_o \cos^2\left(\frac{\pi\theta}{2\phi}\right)\left(\frac{D_o}{x}\right)^2 \quad (4)$$

where x is the axial distance downstream of the orifice, θ is the angle from the orifice centerline, D_o is the orifice diameter, and ϕ is a constant based on the gas specific heat ratio and is 1.7 for CO_2. The CO_2 flow rates introduced into the facility ranged from 10 to 120 sccm although pumping rate data was obtained for mass flows up to 24,750 sccm.

TABLE 1. Sticking coefficients of some common gases as a function of gas and surface temperature. [5]

CRYOSURFACE TEMP. °K	GAS AND GAS TEMPERATURE									
	N_2		CO		O_2		Ar		CO_2	
	77°K	300°K	77°K	300°K	77°K	300°K	77°K	300°K	195°K	300°K
10	1.0	0.65	1.0	0.90			1.0	0.68	1.0	0.75
12.5	0.99	0.63	1.0	0.85			1.0	0.68	0.98	0.70
15	0.96	0.62	1.0	0.85			0.90	0.67	0.96	0.67
17.5	0.90	0.61	1.0	0.85	1.0	0.86	0.81	0.66	0.92	0.65
20	0.84	0.60	1.0	0.85			0.80	0.66	0.90	0.63
22.5	0.80	0.60	1.0	0.85			0.79	0.66	0.87	0.63
25	0.79	0.60	1.0	0.85			0.79	0.66	0.85	0.63
77									0.85	0.63

The radial fin system was instrumented with five temperature sensors to ensure that the panel system was at appropriate pumping temperatures. To determine the pressure at various locations inside the chamber, five Bayard-Alpert type ion gauges were used. The data presented is typically in terms of pressure differences as measured from the facility pressure without gas flow. In this study, CHAFF-IV ultimate pressures were typically below 1.5 x 10^{-6} Torr. One of the ion gauges was attached to a Patterson Probe allowing 360 degree rotation along the chamber length and a tunable distance from the side wall to the chamber centerline, r, as shown in Fig. 5. The angle α is measured from the probe centerline, and $\alpha = 0^{\circ}$ indicates that the probe is pointing towards the cryogenic arrays. In order to accurately assess the data obtained by the Patterson probe, the flow near the probe orifice must be free molecular. Based on Eq. (4), the flow from the sonic orifice can be considered free molecular near the Patterson probe at flow rates below 100 sccm. Much of the discussion for this research will be confined to flow rates in this range.

A cryogenic flat panel pumping surface was also tested in the facility in an attempt to assess any pumping improvement afforded by the finned geometry. Figure 4(b) shows the experimental set up for the flat panel array. In this case, the sonic orifice was adjusted to a distance of 110.2 cm from the panel to maintain constant coverage (~90%) from the sonic orifice between the two tests.

In both experiments, one of the two available 1.0 meter diameter diffusion pumps was used to pump incondensible gases in the facility. The effective pumping speed of the diffusion pump on CO_2 gas was measured to be between 10,600 and 11,800 L/s with a theoretical maximum of about 20,000 L/s without conduction losses.

MONTE CARLO NUMERCIAL MODELING

A computational investigation was used to further understand the pumping characteristics of the radial fin array. The CHAFF-IV array has 112 similar wedge shaped sections. The computational domain involved only one wedge section for simplicity. Free molecule flow was assumed in the volume between the panels which allowed individual molecules trajectories to be followed. Pumping statistics were built from individual particle dynamics to represent the physical problem. Molecules were emitted from a point source on the centerline of the facility a distance of 79.6 cm from the front edge of the fin array. The particles were given randomly selected velocity components in the horizontal and vertical directions based on the distribution in Eq. (4). All surface interactions are treated as fully diffuse implying that the molecules accommodate to the surface temperature. The sticking coefficient can be updated based on the gas temperature and the presumed temperature of the wall from a database based on Table 1 for CO_2. Initially, the incident molecules can either strike the front thickness of the radial fin or enter the volume between two fins. The molecules are followed until they effectively stick to the panel or cross the front plane of the radial array in which case they are considered backscattered molecules. The sticking probability model is based on a Monte Carlo acceptance-rejection scheme. The initial sticking coefficient of 300 K carbon dioxide molecules on a liquid nitrogen cooled cryogenic surface is assumed to be 0.63. [5]

The surface behind the radial fin array is modeled as a flat plate. This surface can either be cryogenically cooled to represent a pumping surface or at room temperature to represent a chamber wall. Results were obtained using both configurations of the back wall. For future CHAFF-IV investigations, the radial fin temperature will be 10-15 K supplied by a gaseous helium cryostat, and the back wall will be liquid nitrogen cooled. Therefore, this model can be used to address future CHAFF-IV configurations without modification.

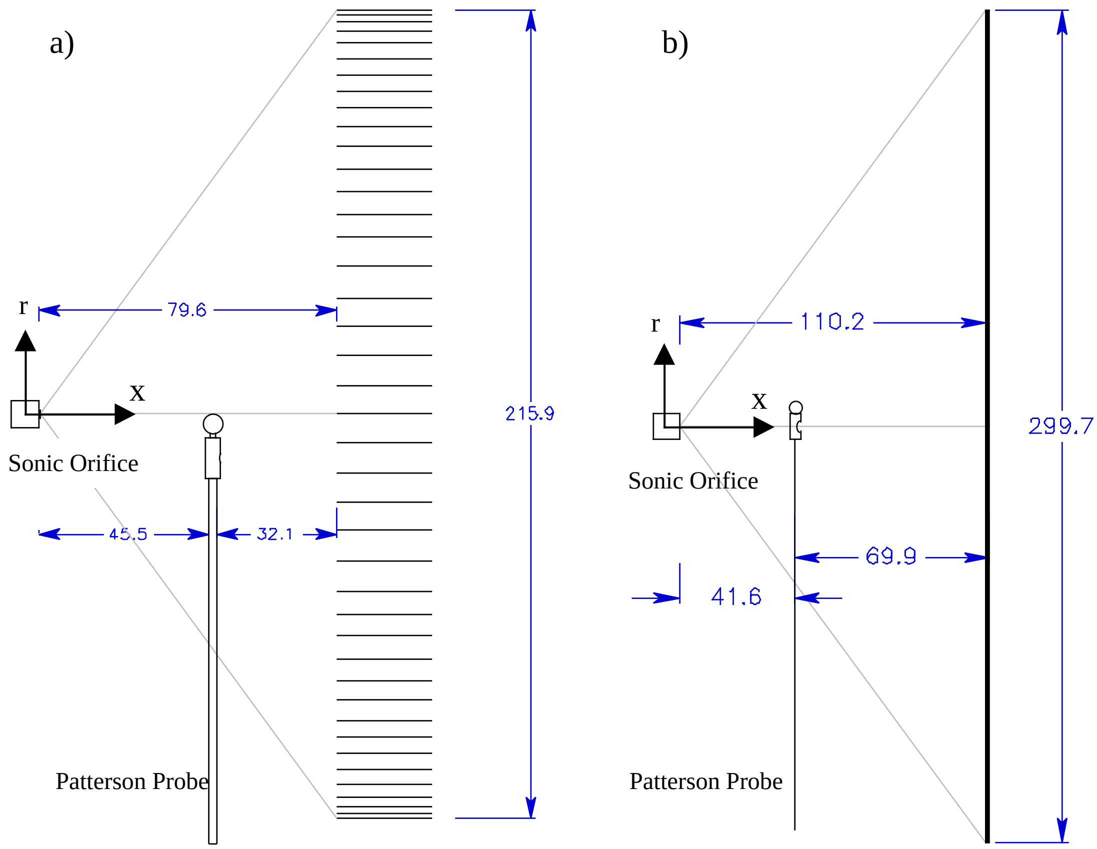


FIGURE 4. Experimental Position of Sonic Orifice and Patterson probe. (a) Radial Fin Array. (b) Flat Panel Array.

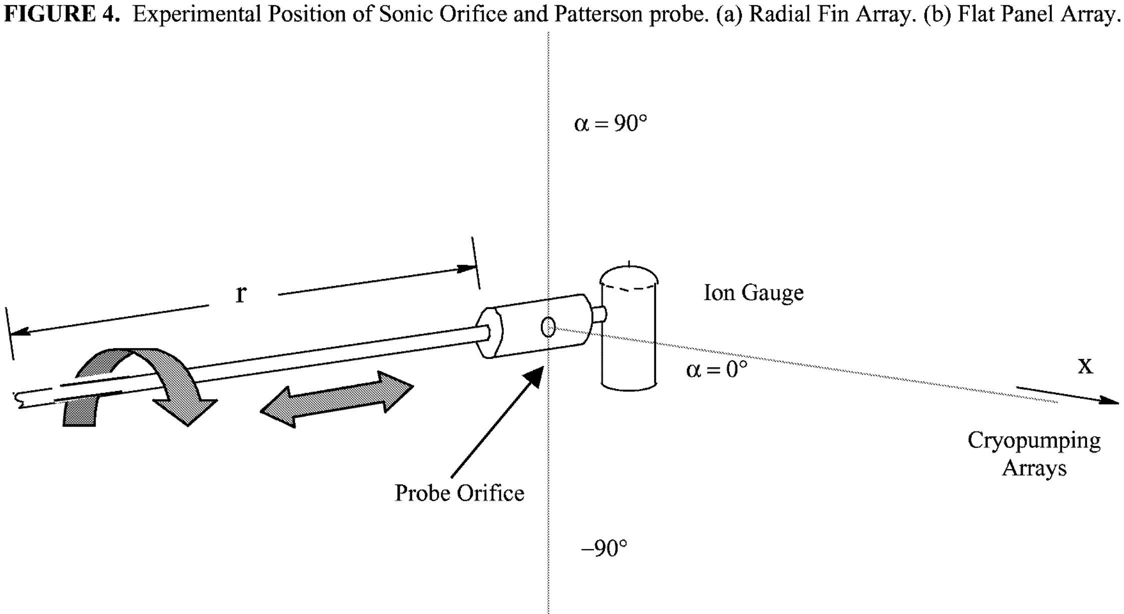


FIGURE 5. Patterson Probe Geometry and Experimental Configuration.

RESULTS

The results of the Monte Carlo simulations for the fraction of backscattered molecules from the radial fin array and the flat panel are shown in Fig. 6 as a function of sticking coefficient. The solid radial fin data line is for simulations which update the sticking coefficient for each interaction with a surface. If the molecule strikes a cryogenic surface and is not pumped, the sticking coefficient becomes unity if the molecule should hit another cooled surface. If the molecule strikes a chamber wall, the sticking coefficient is reset to the original orifice expansion value. The dashed data line is for a constant sticking coefficient throughout the simulation. The radial fin arrays outperform the simple flat panel for free molecule flow for sticking coefficients less than approximately 0.55. As expected, the two radial fin results converge for large sticking probabilities. Figure 6 shows the utility of the radial fin arrays for the pumping of high energy propulsion system flows where the initial sticking coefficients are expected to be extremely low.

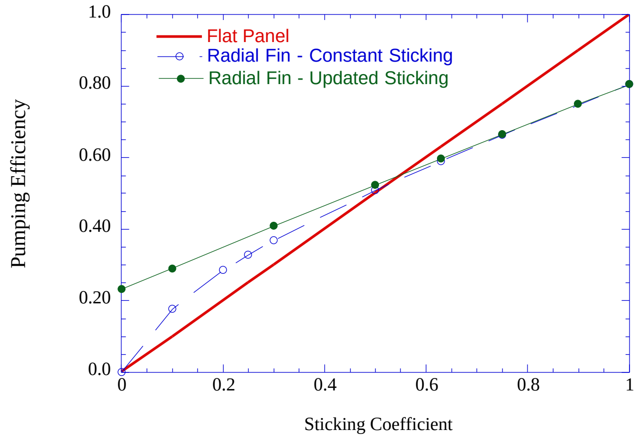


FIGURE 6. Monte Carlo Results for Pumping Efficiency as a Function of Sticking Coefficient.

The measured pressure in the sonic orifice backflow region (i.e. measured at the opposite end of the pumping arrays) was used to determine the pumping rates for the radial fin array. As a function of mass flow, the calculated facility pumping speed was between 0.65 ($\dot{M}$ = 10 sccm) and 2.6 x 10^6 L/s ($\dot{M}$ = 24,750 sccm).

Figure 7 shows the pressure measured at the Patterson probe as a function of mass flow rate at the center of both pumping arrays (r = 0) and at the edge of the arrays (r = 98 cm). The general trend indicates that the radial fin array pumps more efficiently for mass flows up to approximately 60 sccm on the chamber centerline. For higher mass flow rates, the flat panel array outperforms the radial fins. The fact that the radial fins are outperforming the flat panel indicates that the effective sticking coefficient for the experimental results may be below the expected value of 0.63 (Table 1) based on the Monte Carlo simulations. This is possible since the array temperature was measured in the experiment to be between 81 and 88 K.

Above 60 sccm, collisions between plume molecules and backscattered molecules from the pumping arrays begin to become important. Molecular collisions act to return molecules to the arrayss that are not initially pumped. For the flat panel array, the return flux to the array is at a somewhat lower temperature having interacted with the pumping surface once before making the effective sticking coefficient higher as indicated in Table 1. For the radial fin array, the return flux once again passes through the fin geometry and interacts with the chamber back wall at 300 K. The molecules partially accommodate to the chamber wall temperature (depending on the temperature dependent accommodation coefficient); thus, there is not a significant increase in the effective sticking coefficient for the radial fin array. Since the Monte Carlo results assume a free molecule condition, this effect would not be reproduced in the model. A direct simulation Monte Carlo technique is required at higher flow rates.

The fraction of impinging flow on the pumping arrays which is backscattered to the Patterson probe is shown in Fig. 8. The ratio is obtained by dividing the measured Patterson probe pressure at $\alpha = 0°$ by that at $\alpha = 180°$ (i.e. pointed in the direction of the orifice expansion). At 15 sccm, the backscattered fraction from the radial fins is approximately 0.052. This agrees well with a free molecule backscattered fraction of 0.055 derived from Eq. (3).

Figure 9 shows a radial profile for the fin and the flat panel pumping configurations for a mass flow of 20 sccm. This data indicates that the finned array is more effective than a flat panel, and in some cases, the pumping ratio reaches a factor of more than 4. Similar results were obtained for flow rates up to approximately 65 sccm. The data indicates relatively high backscattered flux from the center of the radial fins. This is due to a maximum in incident

flux on the centerline from the sonic orifice expansion and a lack of pumping surface in the center of the finned array due to construction tolerances. The increase in pressure as the probe radial position increases (i.e. tends towards the edge of the fins) can be caused by several factors. First, the width of the radial fins increases as a function of distance from the chamber centerline. Second, the temperature at the far edge of the fins is somewhat warmer (~ 6-10 K) than that near the center of the array due to heat transfer issues making the pumping less efficient. Finally, there is some fraction of the orifice mass flow that does not impinge directly on the pumping arrays due to the high angle gas expansion that can act to increase the background pressure at the array edge.

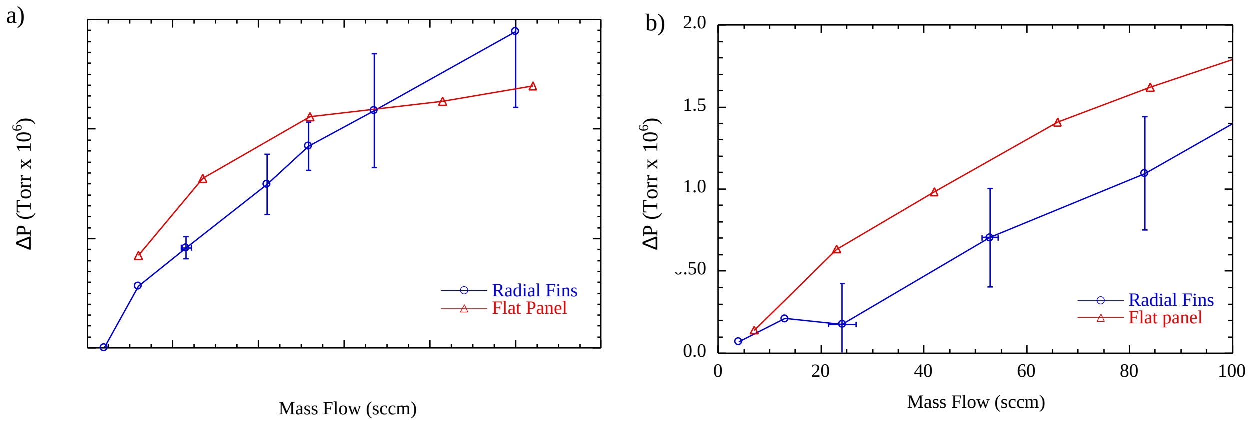


FIGURE 7. Patterson Probe Change in Pressure as a Function of Mass Flow. (a) r = 0 cm, (b) r = 98 cm.

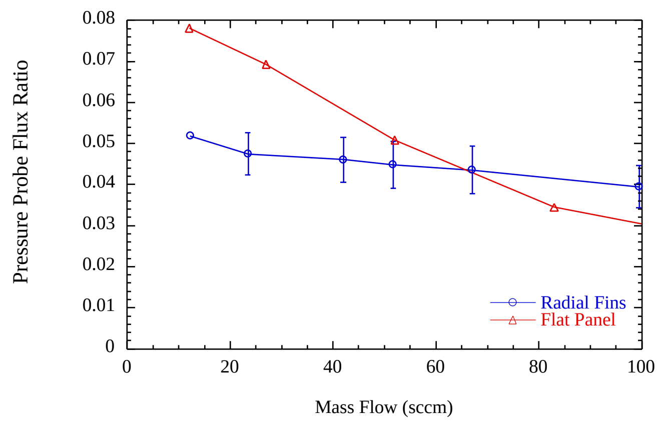


FIGURE 8. Fraction of Backscattered Molecules from Pumping Arrays as a Function of Mass Flow.

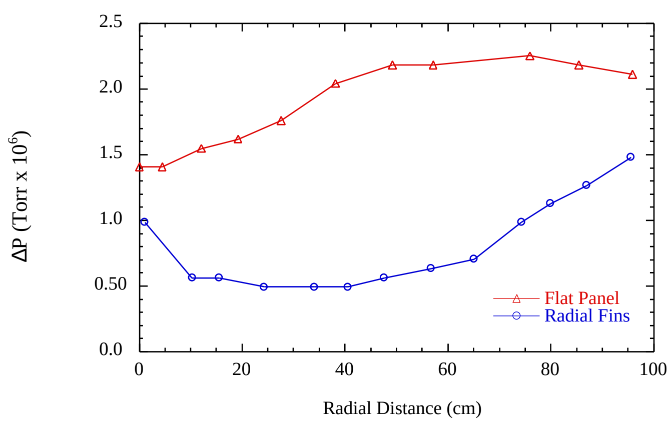


FIGURE 9. Patterson Probe Change in Pressure as a Function of Radial Position for a Flow Rate of 20 SCCM.

Figure 10 shows the angular variation of the Patterson probe data at various finned array radial positions for a mass flow of 20 sccm. As expected, the pressure is minimized for an angle of $\alpha = 0°$ where the probe is pointed directly at the pumping surfaces. There is very little angular dependence of the backscattered molecule population for a position of 98 cm which is near the edge of the finned array. At this location, the pumping is known to be less efficient as discussed previously.

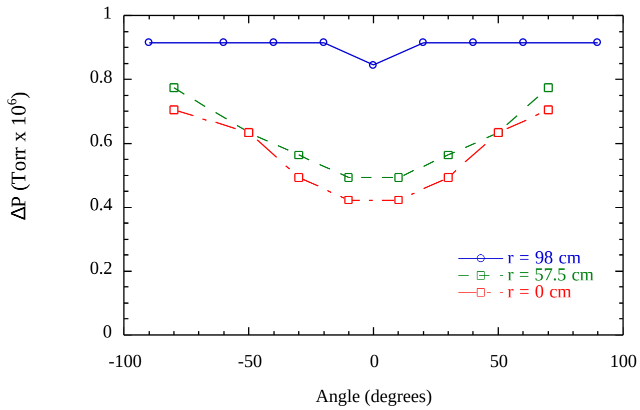


FIGURE 10. Patterson Probe Data as a Function of Sampling Angle at Several Radial Positions for Flow Rate of 20 SCCM.

CONCLUSIONS

Numerical and experimental comparison of the pumping efficiencies of the radial fin array with a simple flat panel array indicates that the radial fins are more efficient for free molecular flows (i.e. mass flows less than 60 sccm on the chamber centerline). The radial fins consistently outperform the flat panel at off-axis positions (i.e. $r > 0$) for the range of experimental mass flows investigated in this study. It is expected that the radial fin array will significantly outperform a flat panel array for thruster efflux at elevated temperatures and for energetic ion flows.

For neutral gas at elevated temperature and energetic ion flows, the radial fin array backed by a LN_2 shield should perform optimally. The sticking coefficient increases for a given surface temperature as the gas temperature decreases. When the radial fin array is at 15-20 K backed by a LN_2 shroud, the energetic molecules will accommodate (at least partially) to the 77 K surface. After scattering from the LN_2 surface with a velocity distribution function characteristic of the surface temperature, the effective sticking coefficient on the radial array will be lower thereby increasing the pumping efficiency.

The pumping rate for the radial fin array ranges from approximately 0.65 to 2.6 x 10^6 L/sec depending on the source mass flow. The experimental configuration utilized approximately 5.6% of the total CHAFF-IV radial fin array. This indicates that pumping rates of approximately 1.0 to 4.5 x 10^7 L/sec should be possible for cold gas flows with the entire facility pumping configuration active. The pumping rates for energetic ions are expected to be similar. Although the rate should increase due to the flux energy to the pumping surface, pumping efficiency decreases are expected due to the sputtering of condensed gases and facility material (graphite protective layers).

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